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Mechanical Behavior of Polycrystalline Rhenium under 3-Points Bending at a Low Homological Temperature

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Abstract. Mechanical behaviour of polycrystalline rhenium under 3-points bending at such low homological temperature as room is discussed. Two metallurgical technologies (electron beam melting and powder metallurgy) were used for the samples preparation. Fine-grained samples (PM metal) exhibit some plasticity prior the failure, while coarse-grained ones (EBM metal) behave like a brittle solid. The intergranular fracture is the fracture mode of rhenium in both cases. Basal slip and prismatic slip of dislocations are not active in rhenium at low homological temperature, but the grain boundary sliding occurs under these conditions. Therefore, polycrystalline rhenium cannot be machined at room temperature despite the growth of grain boundary cracks are braked in the samples due to grain boundary sliding.

1. Introduction

Mechanical behavior of rhenium, which is the refractory metal with HCP lattice, is still unclear [3], in spite of deformation mechanisms in the majority of HCP-metals are well-known [1,2]. The main feature of rhenium is its strongest work hardening under loading that makes it unworkable materials at least at room and elevated temperatures [3,4]. It should be noted that room temperature is a low temperature at the homological scale for rhenium in comparison with other HCP-metals. Mechanical twinning is considered as a possible cause of this anomaly in rhenium [5]. However, rhenium single crystals demonstrate considerable elongation (more than 100%) at low homological temperatures. Both basal slip and prismatic slip are active in the single crystals under these conditions, while mechanical twinning is active, as well [6]. The interaction between twin lamella and grain boundary (GB) may be the reason why rhenium in the polycrystalline state exhibits poor plasticity at low homological temperature [7]. On the other hand, at 1200^{o}C polycrystalline rhenium behaves like an HCP-metal demonstrating considerable plasticity with usual work hardening [8]. Another source of poor workability of rhenium may be its complicated metallurgy namely refining from non-metallic impurities. Indeed, the powder metallurgy technology (PM) is applied for producing of the majority of rhenium goods, such as wire, foil, and sheets [4], despite mechanical properties of a PM metal are lower than properties of a metal from the re-melted ingot. In addition, it is unclear what means a work hardening of the metal, which cannot be plastically deformed, as it takes place in polycrystalline rhenium at room temperature? The rhenium problem continuous to be open till the present time [9].

Such deformation scheme as 3-points bending allows reaching a considerable level of plastic deformation in a metallic sample without its fixing in the grips of a testing machine. It is a very important feature for polycrystalline rhenium, which possesses poor deformability and, hence, it can fail in the grips under loading. In addition, it gives an opportunity to build a stress-strain curve and, hence, obtains information on a work hardening of a material. The aim of this work is the study of the deformation behavior of polycrystalline rhenium under 3-points bending at room temperature that to looking for the possible cause of its poor workability at low homological temperatures.

2. Experimental procedure

Two technologies, which are used by manufacturers around the world, were chosen for the producing of the high pure polycrystalline rhenium in this work. Compacted rhenium sponge or PM rhenium (grain size is about 10 μm) and rhenium sponge subjected by the electron beam melting (EBM) or EBM rhenium (grain size is 5÷10 mm) were chosen as the model materials for mechanical testing. Samples with a shape of a parallelepiped having the size of 30x2x1 mm^3 were cut by means of spark-erosion technique from both PM rhenium and EBM metal. Their deformation behavior was compared with coarse grain Ti4Al alloy (grain size is about 10 mm) because c/a ratio for titanium alloys is close to this parameter for rhenium. Working surfaces of the samples were abraded with a help of abrasive papers and pastes. 3-points bending at room temperature was carried out on Shimadzu™ AG-X 50kN testing machine with Trapezium™ software on Shimadzu™ bending device (the distance between the prisms was 10 mm; the traverse rate was 0,1 mm/min). The parcel consisted of ten samples were tested for each model material. "Stress-strain" curves were built for samples from each parcel. Working surfaces and fracture surfaces of each sample were examined with the help of the light microscope (LM) and the scanning electron microscope (SEM) in the initial / undeformed state and after bending.

3. Results

"Stress-strain" curves of the model materials are shown in figure 1. The total deformation means the deformation prior to the failure of the sample under bending, while the point of maximum on the curve is accepted as the maximal strength of the material. The elastic moduli and the hardening coefficients are automatically calculated by Trapezium™ software. These parameters are given in table 1. No plastic flow stage is observed on the "stress-strain" curve of EBM rhenium, which takes apart after insignificant elastic deformation. Therefore, its mechanical behavior is estimated as brittle. On the contrary, PM rhenium exhibits ductile deformation behavior like Ti4Al alloy, because the plastic flow stage is on the "stress-strain" curve, while its total plasticity is about 4% (curve 2).

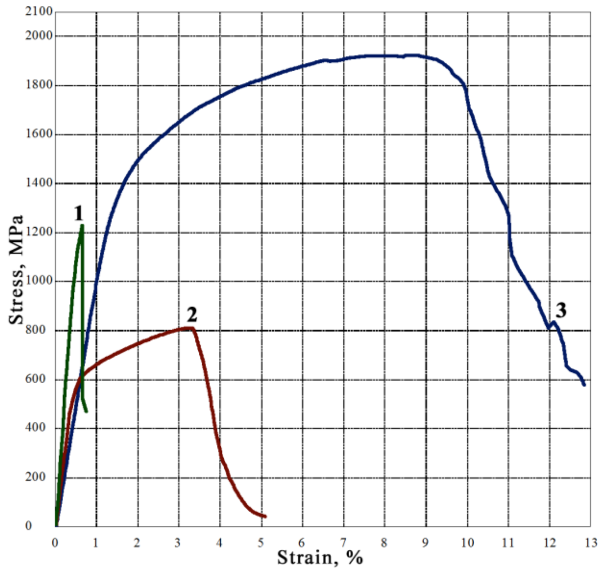

Figure 1. *"Stress-Strain" curves for 3-points bending at room temperature: curve 1a – EBM rhenium; curve b – PM rhenium; curve c –Ti4Al alloy.*

The elastic modulus of EBM rhenium is in two times more than this parameter for PM rhenium, which are similar to the modulus of Ti4Al alloy. This is in agreement with the difference in the mechanical behavior of EBM and PM metals. Ti4Al alloy is considerably more plastic material than PMT rhenium, despite its work hardening is higher. Hence, at low homological temperatures, PM rhenium behaves like a plastic material, while EBM rhenium demonstrates the brittle mechanical behavior. It should be especially noted that PM rhenium does not exhibit considerable work hardening in comparison with the hcp-metal possesses similar c/a ratio. No work hardening occurs in EBM rhenium because it behaves like a brittle solid.

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like a brittle solid. These findings confirm the conclusion that PM rhenium is able to thermomechanical treatment, whereas EBM rhenium is undeformed material at low homological temperatures [3,4,8].

Table 1. Mechanical properties of polycrystalline rhenium and Ti4Al alloy under 3-point bending at room temperature.

Metal	Total deformation, %	Maximal stress, GPa	Elastic modulus, GPa	Hardening coef., GPa
EBM Rh	0.5	1.2	250	-
PM Rh	4	0.8	120	7.5
Ti4Al	12.5	1.9	115	10.5

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Metallographic (LM) examination of the back surfaces has shown that all cracks are localized in the middle part of the area of bending in the sample, where tensile stress is maximal. There are long cracks consisted of merging short cracks in the area of bending (figure 2).The length of the long cracks is compared with the width of the sample. Few long cracks are observed in the samples of PM rhenium, while only one of them transforms into the dangerous crack (figure 2a). The short cracks in PM rhenium are oriented almost normally to the tensile axis of the sample. SEM study of these cracks has shown that they appear on the grain boundaries (GBs), which are oriented normally to the tensile axis of the sample. Morphology of the fracture surface of PM rhenium samples agrees with this conclusion. Fracture mode of PM rhenium under bending is GB fracture, where the surface of grains is rough, that points to some plastic deformation of GBs. However, no any deformation tracks (slip bands and twin lamellas) are revealed inside GBs in the bending area of the sample. The elongation of the PM samples under bending is comparable with the sum of the widths of cracks in the area of bending.

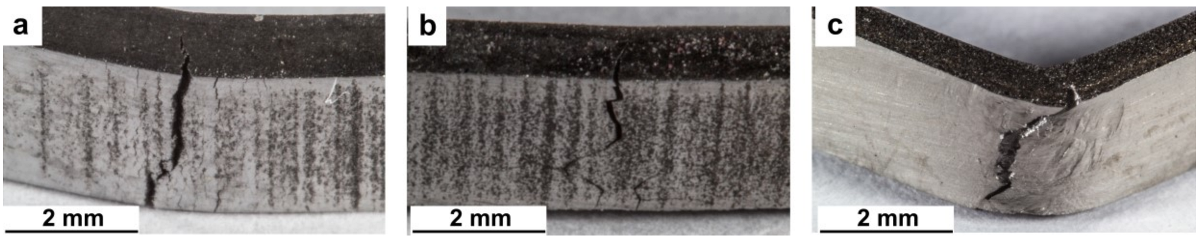

Figure 2. *Cracks in the area of bending under 3-point bending at room temperature: a - PM rhenium; b - EBM rhenium; c - Ti4Al alloy.*

The similar picture takes place in the samples of EBM rhenium under bending. There are 1÷3 long cracks in the vicinity of the middle part of the bending area (figure 2b). Such crack has a broken profile because it consists of GB cracks. The width of GB cracks depends on their orientation to the tensile axis of the sample. The maximal width has the crack oriented normally. Deformation tracks are not observed in the grains near the cracks. It agrees with the brittle mechanical behavior of EBM rhenium under bending. However, SEM examination of its fracture surface has shown that both slip bands and twin lamellas are observed on the almost smooth GBs. The same fracture behavior occurs in the coarse-grained samples of Ti4Al alloy under bending. Indeed, the dangerous crack also has a broken profile insomuch as it consists of cracks advancing along GBs (figure 2c). The difference between EBM rhenium and Ti4Al alloy is in their ability to plastic deformation. The first HCP-material is unable to macroscopic plastic deformation, while the second one is ductile material.

4. Discussion

According to the morphology of the fracture surface, the fracture mode of EBM rhenium under bending is the brittle intergranular fracture (BIF) with some features of GB plasticity. As a rule, BIF is caused by some non-metallic impurities (oxygen, carbon etc), which influence dramatically on the cohesive strength of GBs in a metallic material [10]. In the case of polycrystalline rhenium, this is not the impurity induced GB brittle fracture, because GB cracks are stable at least in PM metal, which demonstrates macroscopic plasticity prior the failure under considerable ultimate strength. Therefore, there should be an additional mechanism (the main one is the cracking) of the stress accommodation in polycrystalline rhenium under bending at room temperature. This is GB sliding that sometimes contributes to the mechanical behavior of coarse-grained HCP-metals [1,2]. Although its contribution to the total plasticity of metallic material is minor, the competition between GB sliding and the cracking can lead to the arrest of GB cracks. Perhaps the same picture takes place in polycrystalline rhenium.

It was shown that the mechanical behavior of polycrystalline rhenium determines by metallurgical technology: coarse-grained EBM rhenium is a brittle solid, while fine-grained PM rhenium is a plastic material. However, in both cases, polycrystalline rhenium cannot be machined at room temperature. No manifestations of plasticity such as slip bands are observed in both EBM and PM rhenium on the microscopic scale. It seems to be that the total elongation of the rhenium samples provides by the sum of the cracks in the area of bending. This parameter for PM metal is considerably high then for EBM metal and, as a result, PM rhenium looks like a ductile substance on the macroscopic scale. The cause of such behavior is that both basal and prismatic slip of dislocations, which provide considerable plasticity in the majority of HCP-metals, do not activate in polycrystalline rhenium at room temperature, whereas GB sliding occurs here. This effect cannot be considered as the contradiction with the empirical knowledge on HCP-metals, which based on the deformation behavior of HCP-metals having melting points lower than 2500ºC [1,2], insomuch as room temperature is very low temperature on the homological scale for refractory rhenium. The study of electronic structure of chemical bonding in rhenium needs for the better understanding of mechanism of its mechanical behavior.

5. Conclusion

Mechanical behavior of polycrystalline rhenium under bending at room temperature is discussed. This refractory HCP-metal cannot be machined at room temperature because dislocation slip is not active in it under these experimental conditions. However, grain boundary sliding occurs in polycrystalline rhenium even at low homological temperature that causes to the stoppage of crack growth in the grain boundaries.

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